Geometric documentation of historical pavements using automated digital photogrammetry and high-density reconstruction algorithms

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A R T I C L E   I N F O

A B S T R A C T

Historical pavements are intrinsic elements of cultural heritage and require the same protection as monuments. Documenting their geometry is necessary for various reasons beyond heritage and historical considerations. Technicians need accurate data from every paving stone because each is unique. The shape any replacement stones must preserve the original slope to ensure that the runoff to sewers is not modified. This process requires much time and meticulous field measurements. Close-range photogrammetry and automatic image correlation, in particular, automatic digital photogrammetry and 3D reconstruction algorithms, make it possible to retrieve precise metric data on irregular surfaces with a high degree of automation. This paper describes the implementation of the structure from motion based photogrammetry methodology applied to the geometric documentation of historical pavements. Technicians and professionals can improve the protocols for historical pavement analysis and conservation. A case study is presented based on a representative section of a street (*Travesía das Dúas Portas*) in Santiago de Compostela, Spain.

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1. Introduction

It is usual to understand cultural heritage as represented in monuments, buildings, historical places and rural works. In urban contexts, historical pavements are less paradigmatic, yet they are a part of the legacy from our ancestors. Presently, 204 cities or urban sites are included in the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage List. Moreover, pavements, in different states of conservation, are considered in all of the cases. Hence, pavements are intrinsic elements of a cultural heritage and must be protected, as are monuments. The value of these public goods is not limited to their artistic and cultural aspects but also favors the economy of their locations (Bedate et al., 2004).

Currently, historical pavements are exposed to multiple external damaging agents that compromise their preservation. The most common threats usually are continuous and persistent over time, although their actual effects are limited (e.g., pollution, climate change, tourism and erosion). Moreover, historical pavements,

because of their nature and condition, tend to be affected more severely by other external agents (Fig. 1), such as:

— Vehicle traffic: The continuous rolling of wheels creates potholes and causes the stone to break.
— Tourism: Performances and cultural events take place in historical sites, and in many cases, this involves the introduction of trailers and other heavy equipment that can cause the movement and sinking of stones.
— The restoration of urban infrastructure: As in the previous case, this activity involves the presence of vehicles and cranes that can seriously impact the pavement.

In general, preventive actions reduce the damage to paving stones but do not stop their deterioration. Thus, the main actions for conservation are the maintenance and restoration of flagstone pavement (removal, replication and substitution of broken or damaged stones). This process of ongoing restoration necessitates precise and adaptable.

In contrast to other monuments, paving stones have particular characteristics that make necessary their documentation for reasons beyond the preservation of heritage. Maintenance of this type of heritage encounters an additional difficulty because each stone is

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Fig. 1. Traffic effects on historical pavements.

bobs and laser distance meters, are all widely used for economic reasons and because their use does not require training (Arias et al., 2005). However, other techniques are gaining support, including the following:

— Topographic methods: This approach requires tachymeters, total stations or robotized total stations (Kvamme et al., 2006). These techniques allow the elements to be digitized and their geometries associated with simple shapes. Each vertex is identified with its spatial coordinates so that joining the points results in a wireframe model. When some of the points are inaccessible (e.g., upper parts of the façade or cornices), it is possible to rely on methods of intersection (Chueca et al., 1996). Moreover, if the device incorporates laser technology, it is possible to measure these distances without using a reflector. This technique is adequate for documenting a site (Yilmaz et al., 2008).

— Modeling methods based on tracking (Beraldin et al., 2000): These methods employ active sensors that directly capture the 3D geometric data of the object through a laser or the projection of light patterns, either structured light (McPerron et al., 2009) or coded light. These devices retrieve the 3D data by applying different measuring principles such as triangulation or flying time. They are robust and costly systems and present complex maneuvering (El-Hakim et al., 2005) with common limitations for field operability. Such systems allow for digital representation of the data of irregular surfaces or curves through the definition of a 3D point cloud of high density. Registering superimposed scanned images (point clouds taken from different locations within the same zone) requires the identification of common points, which is implemented through land laser scanners with limited efficient usability in large zones (Puente et al., 2013).

— Modeling methods based on images or photogrammetry (Remondino and El-Hakim, 2006): These methods are widely used for the 3D reconstruction of architectonic elements (Yilmaz et al., 2008), (Koutsoudis et al., 2013), in archaeology (Ortiz et al., 2010; Hendrickx et al., 2011) and for the modeling of terrain and cities (Aguilar et al., 2005; Gómez-

unique (Fig. 2). At the moment of making repairs, technicians need accurate data on each stone to design a replica for substitution. Specifically, the stones form a part of a whole with a particular slope that cannot be altered because the runoff would be affected. This implies the need for considerable time to take measurements and to develop a detailed planimetric survey of the pavement to differentiate each stone, its surface shape and inclination.

According to UNESCO (1972), the geometric documentation can be defined as the action of acquiring, processing, presenting and registering the data necessary for the determination of the position, shape and size of a monument within a three-dimensional (3D) space and at a given moment in time. That is, such documentation records the present state of a heritage element, providing the basis for the study of its past.

The geometric documentation of heritage elements is implemented through various techniques for data extraction. Manual instruments (Nickerson, 1994), such as measuring tapes, plumb

Fig. 2. Examples of the different singularities of each of the stones in a historical pavement.

Lahoz and González-Aguilera, 2009) as well as monuments and statues (Grün et al., 2004; Barazzetti et al., 2011), among other applications. These modeling methods are easily portable, and their sensors (digital conventional cameras) have a limited cost. However, post-processing of the images to obtain the 3D data that will form the model is necessary. With these methods, it is possible to extract the spatial coordinates of vertices (discrete points) and, in recent years, even easily obtain dense 3D point clouds based on the automatic image correlation (AIC). In both cases, after conducting the point triangulation (discrete or cloud based), it is possible to apply textures and obtain a photorealistic view of the 3D model.

— Some authors have combined these two techniques with the aim of taking advantage of the benefits of each. This approach has resulted in interesting results as related to heritage sites such as the Magdalena de Donatello (Guidi et al., 2004), the Desert Palace in Jordán (Al-kheder et al., 2009) and the Dolmabache Palace in Istanbul (Yastikli, 2007).

The work discussed in this article is focused on the application of the combination of close-range photogrammetry and the AIC software. The continuous evolution of AIC algorithms has reached high levels of accuracy and automation. At present, Structure From Motion and Digital Multi-View 3D Reconstruction algorithms (DMVR) allow for the production of 3D models of high precision and photorealistic quality based on a collection of disordered images of a scene or object, taken from different points of view (Koutsoudis et al., 2013). The high precision of the system (Doneus et al., 2011) and the low deviation of the generated models based on data obtained through laser scanners have been contrasted in studies such as that performed by Rodríguez-Navarro (2012).

This paper discusses the possibilities of the application of the SFM based photogrammetry methodology in the geometric documentation of historical pavements. In particular, the study focuses on one of the most heavily traversed pavements, the granitic flagstone pavement in Santiago de Compostela. Additionally, this paper describes a visual evaluation of the 3D model and the results obtained using the proposed methodology as the main elements of its evaluation. The study compares the results obtained by registered data following three methods: full topographic surveying of the street, the outline of four stones extracted from the 3D models of high precision and the introduction of a particular element in the scene with known geometry, in our case, a level marble stone.

2. Related work on the geometric documentation of pavements

The literature related to 3D geometric documentation with topographic and cartographic purposes is mainly focused on modern pavements, in particular, roads. These studies apply methods based on aerial images (extraction of horizontal road signals (Tournaire and Paparoditis, 2009) or ground images study of asphalt cracks (Ahmed and Haas, 2010), the evaluation of the severity of potholes (Liq et al., 2012) and methods based on tracking (measuring distances in 3D roads through LIDAR (Cai, 2008)).

For these types of elements (pavements, roads, trails, etc.), the application of active sensors (methods based on tracking) usually uses mobile LIDAR technology. We eliminated this method — despite its excellent performance at the surface — because of its high cost and its failure to obtain the required accuracy level (<5 mm). In recent works (Puente et al., 2013), an absolute accuracy level is set at approximately 1–5 cm with a good coverage Global Navigation Satellite System (GNSS) (PDOP <2.5), which can reach 0.3 m with poor coverage.

The methodology that better adapts to the needs of this project is one with reduced cost of equipment and processing, is fully compatible with road traffic and pedestrians, has high precision and visual quality, resulting in a final product that is easily operable by personnel untrained in 3D technologies and has considerable flexibility. Close range photogrammetry meets all of these requirements. It is important to keep in mind that working with large surfaces (e.g., an entire city) with a regular update actualization implies a high degree of automation of data acquisition (Soheilian et al., 2010).

A pavement is an architectonic element that offers a high degree of facility for modeling because of its simple morphology. The main difficulty in modeling such surfaces lies in the photography phase. It is complicated to take oblique photographs from a high location (what is known as a high-angle shot). The fundamental point is to decide at what height the camera needs to be placed to obtain the 3D model. This requires setting the objectives of the spatial resolution and the precision, both vertical and horizontal. The most logical procedure for increasing the resolution and precision of the spatial data is to move the sensor closer to the object (Smith et al., 2010). However, the higher the point from which the images are taken, the wider the surface covered by the photographs, and the work will be more efficient. The height of the camera becomes a compromise between the requirements of precision/resolution and efficiency.

As a platform for raising the camera, the use of masts (Bird et al., 2010; Orengo, 2013) is widely spread in the world of professional photography. Masts are portable and allow good field maneuvering, although it depends on their actual height. Moreover, their use is not affected by weather conditions, a factor that precludes the use of kites (Aber et al., 2002), balloons or airships (Johnson et al., 1990). However, unmanned aerial vehicles (UAVs) are expensive, their batteries discharge rapidly and their rent usually requires the hiring of an experienced operator (Eisenbeiß, 2009).

3. Case study: the historical pavement of Santiago de Compostela

The Old City of Santiago de Compostela was listed as a World Heritage Site in 1985 as one of the best-known locations for Christian pilgrimages. The city is located in the northwest of Spain, (Fig. 3). Although the city was destroyed by the end of the 10th century by Muslims, it was completely rebuilt one century later. Santiago de Compostela has an urban zone that is one of the most beautiful in the world, highlighted by its Roman, Gothic and Baroque monuments. The most ancient of these are concentrated near the cathedral, the tomb of the apostle San Santiago.

Maintaining the approximately $60,000 \, m^2$ of pavement in public spaces within the Old City walls entailed a cost of €236,218 in 2013. Presently, $700-800 \, m^2$ of pavements are repaired annually, strictly within the old center. The main approaches to intervention for the historical pavements are recycling, re-use and rehabilitation. The initiatives for maintenance and conservation of the pavements, for which technical knowledge and protocols for intervention have been developed, guarantee proper conservation, manipulation and modification.

Intervention measures usually are undertaken when a portion of the pavement loses its functionality, that is, when the pavement presents problems that can create risk for pedestrians and vehicle traffic. These actions have to be planned and executed within a few days. Stones that are misplaced, or that are deteriorated or broken, are detected through inspection.

The current economic situation is not strong and thus requires that the protocols followed optimize the rehabilitation costs of the pavement damage. Additionally, these protocols have to address
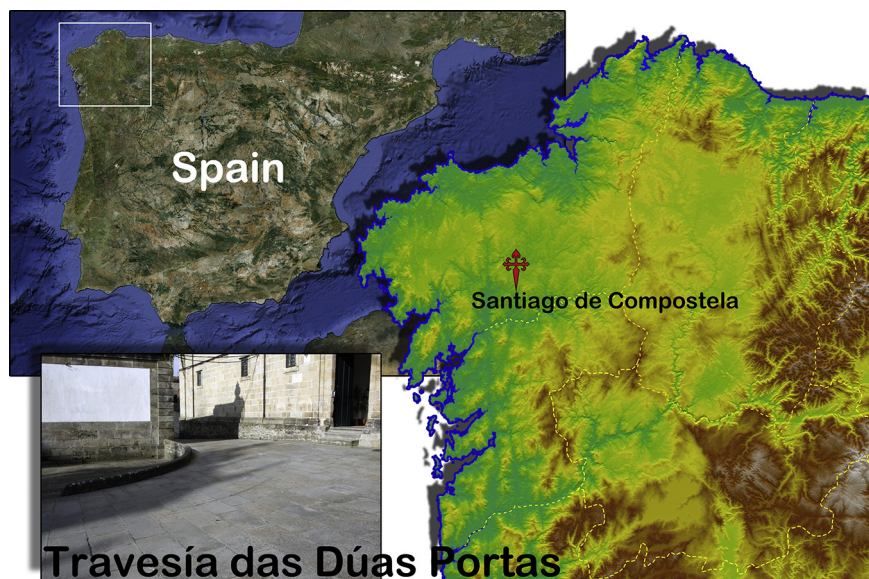
Fig. 3. Location of the Travesía das Dúas Portas.

the quality of future conservation mechanisms. To achieve this objective, a precise topographic planimetric survey is essential. The data obtained through such a survey will guide any necessary adjustment of planning and will enable better control over repair and maintenance.

A 3D model of the pavement provides a useful tool for identifying and describing damage and problems. Moreover, the model facilitates rapid positioning of intervention and supplies data on runoff, trace, geometry, installation registers, façade-ground intersections, etc. All of these aspects are difficult to study with manual data acquisition. In addition, the micro-topography and the small reliefs that make every stone that composes the pavements of the old city center unique need to be considered.

The 3D geometric documentation must measure the contour of each stone with an absolute maximum error of 5 mm. At this precision, quarry workers ensure that nothing more than manual adjustment will be required to fit the stones. With higher errors, power tools (e.g., a circular saw) are necessary, which complicates the logistics of the installation and implies an incremental increase in the final cost.

To study the goodness of the methodology in this type of heritage setting and to evaluate its applicability on a larger scale (e.g., an entire city), a representative section of the street in Santiago de Compostela was selected: the Travesía das Dúas Portas. This stretch is nearly 100 m in length and covers an approximate surface of 450 m^2. The morphological characteristics of the section are representative of the city pavement, with straight and curved sections, areas with different slopes, variable widths, the presence of a sewage system and a sidewalk zone.

4. Photogrammetric equipment

The work in this paper was developed using Agisoft PhotoScan (PS) (Agisoft LLC, Saint Petersburg, Russia). The program is the proprietary software solution for photogrammetric restitution that implements the SFM-DMVR.

Through the SFM-DMVR, the software automatically performs the 3D modeling process based on an image sequence. The program allows for obtaining a set of images taken with any type of camera and from any position. The only requirements are that the object to be reconstructed has to be visible from at least three perspectives

and that the image files contain the EXIF data (manufacturer and camera model, focal distance used in the shot, shutter speed, diaphragm aperture, etc.). The software exclusively elaborates all of the following elements with no human intervention: camera calibration, correction for spherical deformation of the image generated by the objective and the computation of the relative position of each camera (relative orientation). Agisoft PS develops tools for camera calibration (Agisoft Lens) and allows for importing or adapting calibration files generated in other environments.

For shooting the photo, a non-metric digital single-lens reflex (DSLR) camera was used: Canon EOS 400D with CMOS sensor of 10.1 megapixels (3888×2592 pixels), with dimensions of 22.2×14.8 mm and a pixel size of 5.71×5.71 μm. A wide-angle lens of fixed focal length was attached to the camera. The lens is a Canon EF 20 mm f/2.8 with a focal distance and its equivalent in 35 mm of 20/32.5, respectively.

The metric requirements of the project limit the maximum height at 5.50 m for taking photographs. At this height, the pixel size over the ground is approximately 1 mm for the camera type being used. This quality is essential to obtain a reliable 3D model with more than sufficient detail for the two-dimensional and 3D stone restitutions. In this project, a mast that allows a single operator to take the photographs at the maximum height has been used. This elevation system is compatible with the traffic and adverse weather conditions that are common in the city (mainly wind and rain).

To enable shooting the photograph from this height, a device based on masts (Fig. 4) was designed. The device is composed of three sections: a lift telescopic mast (LTM), an aerial poppet-head (APH) and a ground control unit (GCU). The LTM consists of a manually extensible mast composed of light materials (aluminum and plastic). The maximum length is approximately 7 m (from this height upward it is convenient to have two operators). The APH is mounted on top of the higher end of the LTM and consists of a mobile aluminum structure on top of which the camera is placed. The AHP supports the camera movement around the vertical axis based on a string system. Moreover, the AHP incorporates a remote-control trigger and a video transmission system, both activated through a wire line. The GCU is composed of a screen that supports the visualization of the camera focus (through the live-view features in the camera) and a wired remote-control trigger. The whole

Fig. 4. Mast usage in photograph shooting.

system was designed to be run by a single operator with a harness where the system is anchored.

To scale, orient and georeference, a total station Pentax R-326EX and a mini prism (effective diameter: 24 mm) were used.

5. 3D photogrammetric modeling process

The proposed methodology follows the guidelines established by (Ortiz et al., 2010): design, 3D measuring, structuring/modeling and texturing/visualization and accuracy evaluation of the 3D photogrammetric models.

5.1. Design

The design is the most critical phase in the elaboration of a high-quality 3D model. It is always convenient to perform an inspection of the work zone to ensure that the methodology is applicable with no restriction. This phase encompasses the capture of the photographic set-up to the realization of the external orientation of all of the images (to determine the camera positions during the photograph shooting), including the scaling, the rotation and the georeferencing of the set.

In contrast to software that uses multi-image photogrammetry, with PS, it is not necessary to calibrate the camera beforehand or to manually identify the homologous points. However, it is possible to increase the accuracy slightly based on a previous calibration. In this work, a calibration was generated by one of the most precise photogrammetry programs: PhotoModeler Scanner (PMS) (Eos Systems, Inc., Vancouver, Canada). One specific routine within the Agisoft lens framework transforms the calibration data computed with PMS and adapts it to PS. This creates a new calibration file with XML extension.

The pavement modeling with PS does not require the use of coded targets or markers. The targets that appear in the images are not recognizable by the software and are placed in the scene with the sole intention of generating a complementary work of precision with different restitution software.

The photogrammetric solution is based on aerial images but they are taken at street level. Thus, is possible to obtain better coverage, visibility, precision and resolution. The image acquisition is entirely performed with the camera placed on top of the mast and configured at f11 and ISO 400. It is important to establish these values correctly. Under limited light conditions, the shutter speed decreases, and the photos can be blurred and therefore unusable. The photographs must be taken in the usual RAW format. This format contains the entire image data as captured by the digital sensor. This avoids losing data or variations caused by compression that can affect the automatic image correlation (AIC).

The APH is configured to obtain aerial oblique photographs so that the photographs capture the ground in front of the operator, from his feet to the opposite side of the street. The photographs are taken with approximately 1 m of separation. The operator moves laterally, with his back against one of the adjacent street walls. That is, for a street of 100 m, one photograph is taken every meter, 100 photographs per side, resulting in 200 photographs.

This methodology is extensible to streets with a maximum width of 8 m. When this value is exceeded, it is necessary to perform intermediate cross-width photographs, in addition to the lateral sweeps. For instance, a 100 m street that is 16 m wide, it will be necessary to perform two lateral sweeps and a third one following the central longitudinal axis of the street, taking photographs of both sides. This will result in approximately 400 photographs along the 100 m. In summary, as a general rule, it is necessary to perform longitudinal sweeps separated by 8 m at most.

Before loading the photographs into PS, it is necessary to develop them in a compatible format: JPEG, TIFF, PNG, BMP, EXR, PGM, PPM or MPO. Among the free tools, the most recognized are RawStudio and RawTherapee. Among the proprietary tools, Adobe Photoshop (Adobe Systems Incorporated) and Aperture (Apple) are the best known. In this study, all of the photographs were exported automatically to JPEG.

The photographs exported to JPEG are loaded directly to the program, along with the calibration XML file. Thus, it is possible to start the workflow automatically. The first phase consists of

determining the homologous points of all images. This results in determining the image external orientation (i.e., the part of the camera from which the image is taken). The process ends with the generation of a disperse cloud of homologous points. At this stage, is possible to inspect the relative position of the cameras and check that no errors are visually noticeable. When the camera position is known, it is possible to indicate the control points over the ground (Ground Control Point; GCP). These GCPs have to be clearly identifiable and have to coincide exactly with those measured with the total station. Each GCP is assigned the coordinates determined by the total station to determine the scale, the position in the scene (georeference) and the rotation.

5.2. 3D measurements

Obtaining the 3D measurements consists of an automatic routine that instructs the program to compute the dense point cloud that defines the granitic flagstone pavement. This step is performed based on the set of photographs and the automatic image correlation. In contrast with multi-image photogrammetry, PS is not able to configure the cloud parameters beyond what is designated quality (from low quality to very high quality). The quality determines the size of the group of pixels that will be used for comparison of the photographs. The higher the quality, the smaller the number of pixels per group and the more detailed and precise the resulting geometry will be, thus, the more the accuracy of the cloud and the 3D model respect the original object. This requires an increase in the processing time and more resource consumption. In many cases, the maximum quality of the grid is determined by the hardware limitations rather than the input data because the images have a high pixel count.

The program does not allow us to visualize the point cloud (although it supports its export it in a later stage). The process continues to the next stage: structuring and modeling.

5.3. Structuring and modeling

The automatic routine described in the previous section results in a polygonal grid generation or surface. Polygons are usually the most flexible path to represent the results associated with 3D measurement and correspond to an optimal surface representation (Remondino and El-Hakim, 2006). This step implies automatic triangulation of all of the points to obtain a 3D triangular grid.

During this process of reconstruction of the 3D geometry model, the SFM-DMVR software guarantees that no human intervention is necessary. All image external orientations are known in advance.

5.4. Texturing and visualization

After completing the polygon grid, the results can be visualized as a cloud of points (Fig. 5A), the wireframe and the monochromatic shading (Fig. 5B) or color shading. In the latter case, the values of the RGB colors inside every triangle are tied to the surface of the model.

In addition, it is possible to automatically generate a photorealistic texture by integrating the color data with the 3D model (Fig. 5C). The most adequate resolution can be defined according to the purpose of the model. Resolution is upper-limited by the resolution of the original images used in the process.

5.5. Evaluation of the quality of the 3D model

5.5.1. Uniformity

The generation of a 3D model of an element or scene implies obtaining an accurate digital replica that retains all of the
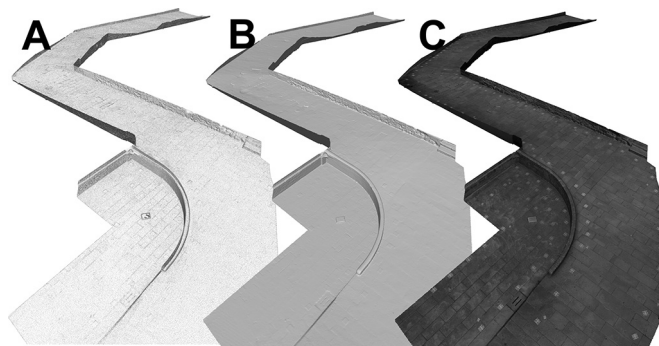

Fig. 5. Visualization of the 3D model: point cloud (A), monochrome polygonal surface (B), polygonal surface with textures (C).

morphological specifics of the original. The model must be complete, and the existence of zones lacking data (gaps within the point cloud) must be considered as a negative aspect. For this particular case, the geometric documentation of the historical pavements must allow the identification and measurement of all of the stones. To make PS capable of fully restituting an irregular surface (that is extensible to any software based on SFM-DMVR), all of the faces must be captured by at least three photographs taken from three different positions.

5.5.2. Metric quality

To evaluate the measuring quality of the 3D reconstruction, three tests were developed.

The first test analyzes the differences between 32 check points uniformly marked along the 3D model. This is done with respect to the measurements obtained by the total station and for these sets of check points. The results are shown in Fig. 6.

The second test evaluates the correspondence between the contours of the granitic stones in the 3D model and the real contours. For that purpose, the analysis relies on photogrammetry to generate the individual 3D models of four stones belonging to the section of the street studied in this work. The four models were generated through approximately 8–10 photographs at a distance of 1.2 m. An analog Vernier is placed in the center of each stone at the maximum aperture. This implements the model scaling and defines a reference to evaluate the metric quality of each model. Error analysis reports that the average quality is below 0.10 mm (average error and standard deviation less than 0.0001 m). Therefore, the measurements are accepted as valid.

A total of five different polylines were drawn over each of the individual models based on markers clearly defined on the stone texture (cracks, corners, spots, etc.); different software was used for this purpose. This marking process was repeated on the five polylines on each of the stones in the 3D model of the stretch. Finally, the distances of each stone for the 3D individual model and the general model are compared. The results are presented in Table 1.

The third and final test analyzes the accuracy of the representation of the micro-topography of the stones. A marble stone in a random position was placed in the scene. This stone is of similar dimensions as the paving stones, and it is leveled and has a perfectly plain surface. The leveling process was performed in the field through adjustments of three threaded bars where the stone is placed and two spirit levels. A total of 30 random points distributed over the 3D model surface were also extracted. The deviation of the Z coordinate was also analyzed (Fig. 7). The results are shown in Fig. 8.
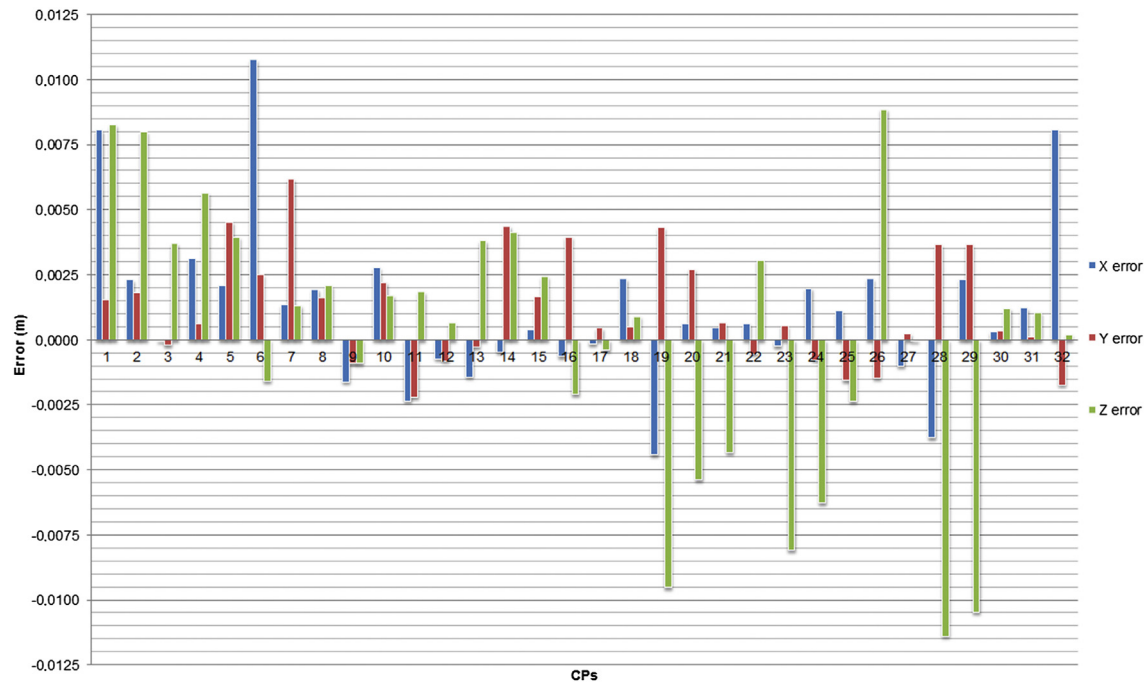
Fig. 6. Differences in coordinates X, Y and Z of the 32 checking points (CPs) measured with the total station and the PS software.

5.5.3. Visual quality

The visual quality of a 3D model is a subjective determination. However, this aspect is of interest because it allows consideration of the applied texture, the presence of morphological imperfections and the visual accuracy of the model independently of the selected point of view.

Texture is one of the most significant aspects associated with evaluation of visual quality. During the process of integrating the color data into the model, several errors can occur. The most common error is the presence of zones without texture because of

Table 1
Differences in the polyline lengths measured over the 3D individual models of each stone and those measured over the 3D general model.

Stone	True dist. (m)	3D mod. dist. (m)	Error (m)
Stone 1	0.739	0.739	0.000
	0.623	0.626	−0.003
	0.462	0.463	−0.001
	0.866	0.863	0.003
	0.548	0.548	0.000
	0.530	0.532	−0.002
Stone 2	0.431	0.430	0.001
	0.440	0.439	0.001
	0.413	0.411	0.002
	0.659	0.661	−0.002
	0.509	0.511	−0.002
	0.610	0.610	0.000
Stone 3	0.753	0.755	−0.002
	0.756	0.760	−0.004
	0.638	0.637	0.001
	0.622	0.625	−0.003
	0.530	0.533	−0.003
	0.716	0.713	0.003
Stone 4	0.360	0.362	−0.002
	0.290	0.288	0.002
	0.573	0.570	0.003
	0.275	0.273	0.002
	0.892	0.892	0.000
	0.651	0.654	−0.003
		Total Error (m)	0.000
		Stand. Dev (m)	0.002

the lack of pictographic data. The symptoms are easily identifiable: stretching of the contiguous texture, application of a plain color (usually black) or double projection (Al-kheder et al., 2009), among other anomalies. The latter occurs when the texture is applied twice, once over the correct part of the element and the other over a hidden part for which no pictographic data are available. Radiometric differences caused by variations in luminal conditions during the photograph shoot (Apollonio et al., 2012) or errors in color determination caused by reflection and glare (Trinchao et al., 2012) are other commonly observed defects.

After texture analysis, it is necessary to address shape defects in the model. A model with monochromatic shading allows for better evaluation of the accuracy and detail level. The most common defects are bulkiness; isles or irregular forms that are nonexistent in the real object and that are usually generated during the surface reconstruction because of a high noise level within the point cloud (an anomalous group of points that deviate from the normal
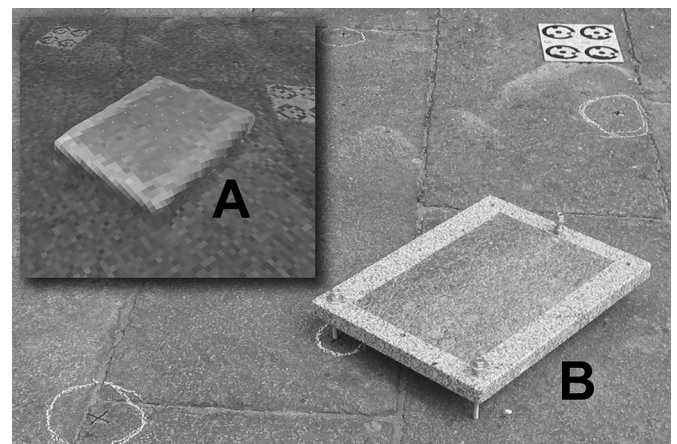

Fig. 7. Evaluation of the micro-topography over a marble stone: 3D model with 30 checking points (A), marble stone photograph (B).
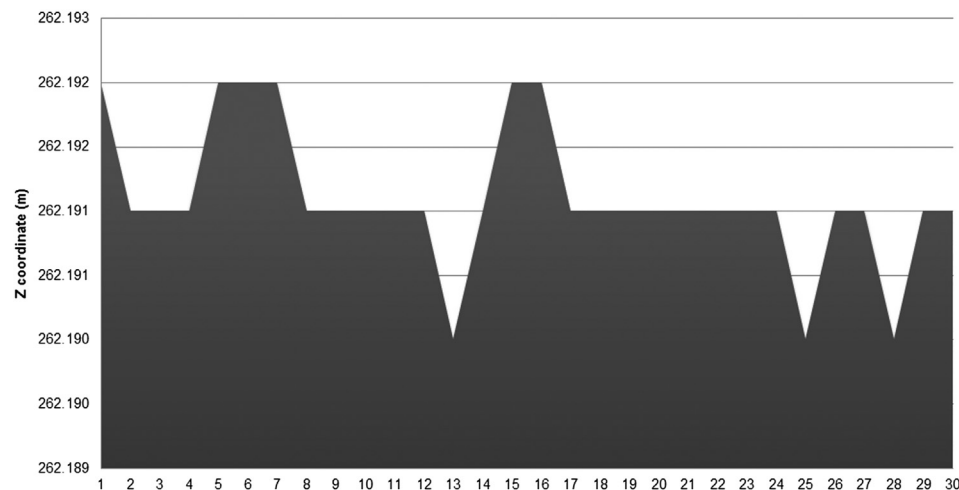
Fig. 8. Representation of the Z coordinate of the 30 checking points randomly selected.

continuation of the cloud); wave defects in the polygonal surface; and polygons of large size (in relationship to the remainder of the model), originating during the reconstruction of the grid and caused by the gap filling (zones with no data).

6. Results and technical discussion

The 3D modeling process of a stretch of 100 m of historical pavement was satisfactorily achieved following the low-cost SFM based photogrammetry methodology. Metric data of the entire stretch through the generation of a polygonal grid were gathered. This representation is accurate with a detail level that makes it possible to detect the stone joints and their micro-topography. Over this polygonal surface, a photorealistic texture of high quality and with a resolution of one pixel per 1.1 mm was applied.

With the aim of evaluating the product developed in this study, it is necessary to review the simplicity related to cost, the precision of the photogrammetry related to quality and the validation and utility of the 3D model. These three considerations are necessary so that the presented methodology can be generally applied in heritage research.

6.1. Simplicity and cost

The technique described in this paper aims to create the 3D model of a representative stretch of a historical pavement. The technique has to be simple, methodological and easily reproducible at a larger scale.

An entry camera with a lower resolution sensor than more modern sensors was used. This allowed us to demonstrate that close-range photogrammetry does not require the use of high-quality cameras. Compact, or bridge cameras or even mobile phone cameras could be used. The tendency toward using reflex-type cameras lies in the larger size of the sensor, the possibility of employing a lens of high quality and manual controls. The cost of such a camera including the lens is approximately €1200.

The mast is a suitable solution for taking photographs at a height. The device has a relatively low cost (less than €100), and it does not present any limitation to use. It is easily portable because of its light weight, and it can be collapsed to less than 2 m of length. The field maneuvering is relatively easy using its harness and anchorage system, and the mast allows for the operator to freely switch between different positions for shooting photographs in a rapid and agile manner.

The proposed approach covers the total surface of the pavement, including the ground-façade juncture, with extensive overlap (close to 75%). This guarantees a high degree of detail. The approach has been defined for streets of at most 8 m in width. Guidelines from wider streets or even squares have also been proposed, obtaining 222 photographs that cover 450 m^2 of surface in 2 h.

The topographic surveying can be performed before or after shooting the photograph. In any case, the GCPs must be clearly marked so that they can be correctly reproduced in both systems. A total of three GCPs have been used for the street section under study. The approximate cost for a surveying of such characteristics is approximately €900 per hectare.

Most of the material costs result from the purchase of software and hardware necessary to generate the 3D models. The cost of professional version of the Agisoft PS is €2700, which is a noticeable price but far below that of other technologies with similar results. The hardware to process 500 to 1000 photographs will have a cost of approximately €1000. The processing time to obtain a 3D model with photorealistic texture and georeference is approximately 6 h in the corresponding computer. Increasing the investment to €3600 reduces the processing time considerably.

In summary, to generate the 3D modeling of 60,000 m^2 of the historical city of Santiago de Compostela would require 134 days. The total cost, including the material, personnel (1 technician) and the topographic surveying, would be approximately €30,000. These investments do not take into account industrial profits, general costs and the Value Added Tax (VAT).

6.2. Photogrammetry accuracy and quality

Regarding uniformity, the multi-image photogrammetry based model generated in this study ensures that any surface zone of the pavement appears in at least five photographs taken from five different positions. Moreover, the model ensures that the density and size of the triangles are kept constant along the surface.

The accuracy of photogrammetry is sufficient for the metric needs required for this project. The average error in the checking points measured by the total station and PS is 5.5 mm, and the standard deviation is 3 mm. Regardless, it has been observed that differences in the measurements in the second test (average 0 mm and standard deviation of 2 mm) or in the study in the Z coordinate

(standard deviation of 1 mm) are minimal. In these two tests, the reference system that has been used in each case is clearly several orders of magnitude more precise than the 3D model of the section of the street. The data taken with the total station, with an estimated average error of 3–4 mm, are adequate as a reference system to scale, orient and move the model but are not suitable as a control system.

Regarding the visual quality, the 3D model presents some of the problems previously described. However, these problems can be resolved to a large extent. The most notable issue is the presence of radiometric differences in the texture, which originate in the continuous data gathering through the course of the day. PS allows the computation of the average color of the pixels in the photographs from each zone, which drastically reduces the variations in texture. Another problem associated with this work is the presence of elements unrelated to the purpose of the study of the photographs. The majority of these elements are people and vehicles. It is possible to instruct the program to ignore portions of the affected photograph through the use of masks. However, this implies an increase in office working time. The recommendation would be to avoid capturing photographs until the area is clear (this can be checked at any time by the operator through the display installed in the GCU).

The pavement model does not present any volumetric defect, mainly because of its simplicity. The noise level is nearly absent, and neither bulkiness nor deformations appear. The geometry of the photogrammetric network (the positions of the cameras) favors a detail level that is identical to the totality of the surface. This allows detection of the stone joints and their micro-topography.

6.3. Validity and utility

With this technique, it is possible to develop an adjusted plan with more control over the interventions for repairs and maintenance. The SFM based photogrammetry products also improve decision-making and facilitate the determination of the location, recognition and description of damage. Moreover, this method
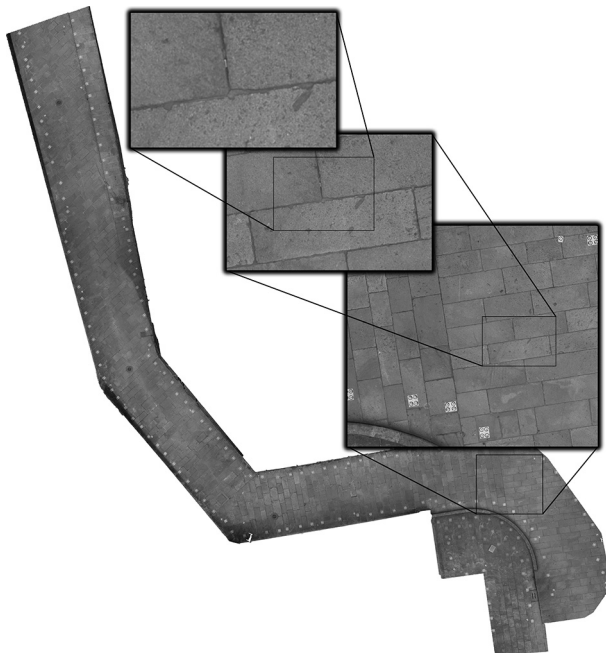

Fig. 10. Example of 3D restitution performed over a portion of the digital model.

provides information on such features as runoffs, trace and registering of installations, and all of this can be accomplished without fieldwork.

Based on digital geometric documentation (the 3D complete model), it is possible to generate a variety of products that improve the analysis of historical pavements. The orthophotos represent the first attempt (Fig. 9). As mentioned previously, the resolution depends extensively on obtaining the maximum resolution available (1.1 mm per pixel), which has a direct impact on the quality. In this study, a georeferenced orthophoto has been generated of the 450 m^2 area with the highest possible resolution, resulting in a 916 MB image, in which it is possible to detect many details. Regardless, in many cases, it is interesting to obtain a planimetric survey that simplifies the reality, and the orthophoto is a perfect basis for imaging the stone borders in 2D with a high level of detail and
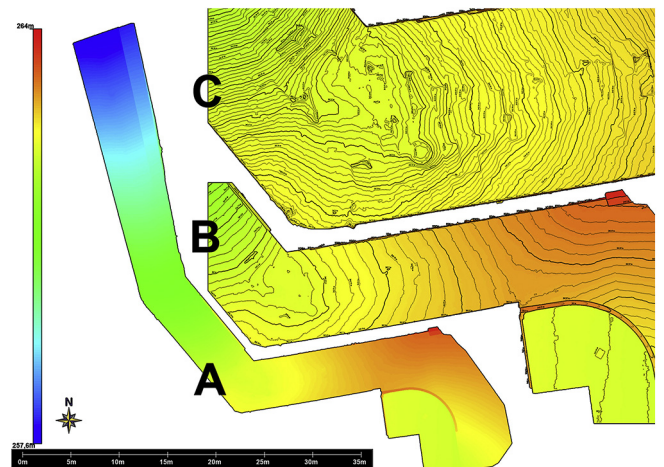

Fig. 9. Georeferenced orthophoto generated through a 3D model. Different degrees of zoom are shown to demonstrate the image quality.

Fig. 11. DEM section generated by the 3D model (A). Examples of contour lines with different intervals: 5 cm (B) and 1 cm (C).

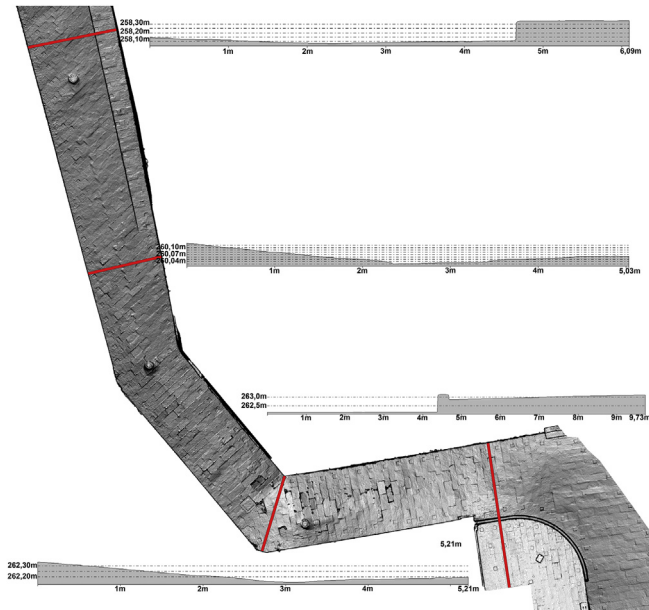**Fig. 12.** Cross sections over the 3D model.

Fig. 14. Runoff plane (A) and the corresponding contour lines (B).

precision. It is also possible to create a 3D drawing directly on the exported digital model (OBJ, VRML, KMZ, etc.). This requires additional commercial software, which is sometimes available free of charge (e.g., 3DVEM) (Fig. 10). The generation of digital elevation model of terrain (DEM) (Fig. 11A), the section definition (Fig. 12), the computation of contour lines (Fig. 11B and C), slope planes (Fig. 13B), orientation planes (Fig. 13C), runoff planes (Fig. 14) or the possibility of exporting to interactive formats such as PDF3D (compatible with Adobe reader) are examples of derivative products.

7. Conclusions

After analyzing the 3D modeling results of the pavement stretch in the Travesía das Dúas Portas in Santiago de Compostela, it is possible to conclude that the use of the close-range photogrammetry, combined with a mast, is an option that is highly interesting for the geometric documentation of heritage elements. The results at the metric level are far above the limitations indicated by maintenance technicians. Moreover, the possibility exists of performing a photogrammetric surveying without interfering in the regular routine of the city. The results are in accordance with previous studies that consider work costs and execution times (Rodríguez-Navarro, 2012). This supports the use of the low-cost SFM based photogrammetry methodology for 3D documentation over other 3D modeling techniques. In terms of financial investment, amortization, the time required for data gathering and the time for office post-processing, the proposed approach is highly competitive. The data gathering with this approach is more agile and rigorous during the inspection and avoids the relocation of the
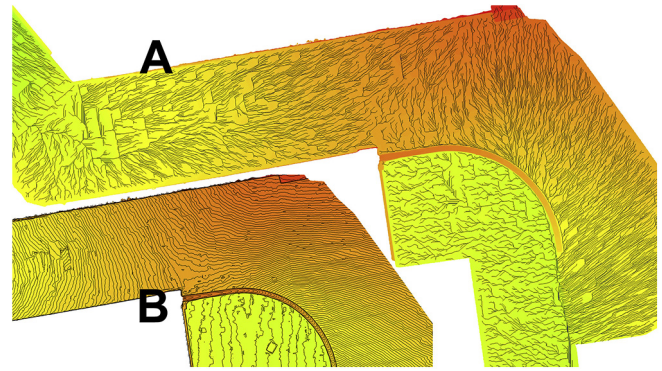
operator. All of this clearly impacts the management of the interventions.

Using a mast is essential for obtaining oblique photographs of high quality. Its simplicity and ability to maneuver in the field have been satisfactory, and it has allowed establishing a homogeneous photogrammetric network that has a direct effect on the volumetric quality and the esthetics of the model. With the pictographic data, Agisoft PS is capable of generating a 3D model of high quality and with a uniform polygon density along all of its extensions. The textures have a visual quality of very high resolution and are reliable (which is fundamental to performing precise drawings). This is critical because the textures represent the starting point for the entire 3D reconstruction process. To create similar textures in models obtained through a grid based on laser scanner laser, the process of post-production requires a lengthy phase of elaboration and management of different types of software, which is necessary for both the calibration and the orientation of the camera to create the texture maps and their final projection (Rodríguez-Navarro, 2012).

The requirements of the project have allowed reducing the number of triangles of the mesh at a moderate level. Starting with the same pictographic material, PS would be capable of elaborating a model with two higher grades of precision: high and very high. These two levels correspond with an improvement in detail of each stone at the micro-topography level (roughness detection, fine cracks, etc.) but do not suggest an improvement in the project's needs. However, the automatic pixel comparison at this detail level requires powerful hardware, and the time consumed in the model generation would be much longer.

In addition, the number of triangles in the grid was restricted to 10 million because of hardware limitations. Otherwise, the computer would malfunction when displaying the data. Subsequently, the number of triangles (2 million polygons) and the resolution of textures (16,000 × 16,000 pixels) of the orthophoto were reduced for exporting this model to make it available to other researchers. Thus, a model of several million polygons and large texture files can be studied by a specialist with limited knowledge and means.

One of the most important and necessary tasks for the technicians in charge of the metric documentation is to bring the product closer to the client and demonstrate how to extract useful data. Moreover, the metric aspect must be emphasized in contrast with pure esthetics.

Therefore, the SFM based photogrammetry methodology is valid and highly recommendable for the extraction of metric data. Technicians and professionals can improve the protocols for historical pavement analysis and conservation. The experiment performed in Santiago de Compostela is extensible to any other historical city.
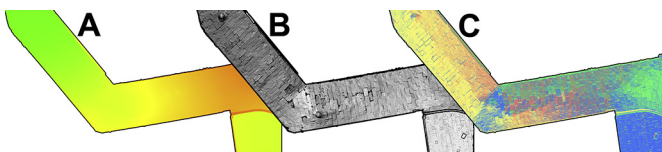

Fig. 13. DEM (A), slope plane (B) and orientation plane (C) of a section of the Travesía das Dúas Portas.

Acknowledgments

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